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Flow equation and similarity criterion during centrifugal casting in micro-channel

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Abstract: Liquid metal filling flow process in the microscale during the centrifugal casting process was studied by means of similar physical simulation. The research was focused on derived similarity criterion. Based on the traditional flow equations, the flow equation and the Bernoulli's equation for liquid metal flows in micro-scale space were derived, which provides a mathematical model for numerical simulation of micro-scale flow. In the meanwhile, according to the micro-flow equation and the similarity theory, the similarity criterion for the physical simulation of the mold filling behaviors was presented under centrifugal force field, so as to achieve the visual observation and quantitative analysis of micro-flow process.
Key words: micro-channel; micro-flow; centrifugal force field; similarity criterion

1 Introduction

In recent years, research on the micro precision casting technology has attracted much attention globally [1−5]. By means of the centrifugal casting process, BAUMEISTER et al [1,2] successfully produced micro-scale gears and YANG et al [6] produced micro-rod with a minimum diameter of 100 μm and a aspect ratio of 200. In the micro-casting process, many micro-scale effects, which are normally ignored in traditional casting process, such as surface force and size effects, are highlighted. This could lead to different flow behaviors in micro-channels compared with that in the macro-scale channel. The previous studies on the room temperature micro-scale flow principles of the fluids, such as water, oil and gas, have shown that micro-scale fluid flow was different from that at conventional macro-scale [7−9]. The flow behavior of liquid metal has a significant impact on process design and product quality of micro-casting. Therefore, it is of great importance to understand the flow behavior of liquid metal in the micro-scale cavity, which is highly favorable for improving the product quality of the micro-casting process [10]. At present, numerical simulation method has been widely used in the study of mold filling behavior in macro-scale centrifugal casting [11−14]. However, the numerical simulation can provide only qualitative analysis, but not visual observations. The physical simulation method based on the similarity theory was developed [11,15], to achieve both visualization and quantitative analysis.

Nevertheless, there is a lack of understanding about the liquid metal flow behaviors in the micro-scale cavity during the novel micro-scale casting process. In the present work, based on the flow principles for traditional casting process and the physical condition of micro-casting process, the liquid metal flow equations and the Bernoulli equations for the micro-scale centrifugal casting process are derived. These equations could provide scientific basis for the research on the visualized physical simulation.

2 Liquid flow equation of micro-scale space in centrifugal force

In micro-casting process, the liquid metal flow behavior is equivalent to that of non-isothermal and

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non-steady-state Newtonian fluid. Due to the scale effect, the flow behavior shows the following characteristics: more pronounced surface force (surface tension and gas counterpressure, etc.) effects, less mold heat storage capacity, increased cooling rates of liquid metal, increased viscosity of the melt. In this work, gypsum is used as the mold material, and the mold is preheated. The following assumptions are made in the current model:

1) The liquid metal flow is continuous in the whole flow process;

2) The liquid metal is incompressible;

3) The dynamic coefficient of viscosity of the liquid metal is constant;

4) The surface tension coefficient does not change with temperature.

2.1 Liquid metal flow equation of macroscopic scale under gravitational field

The Navier−Stokes (N−S) momentum equations are used to model the macro-scale mold filling behavior of the liquid metal under gravity field:

$$\rho\frac{Du}{Dt}=\rho F_{\mathrm{M}}-\nabla p+\mu\nabla^2 u \tag{1}$$

where u is the velocity; ρF_{M} is the mass force applied on a unit volume of fluid; μ is the dynamic viscosity coefficient; p is the pressure of a point (x, y, and z) in the flow field .

2.2 Liquid metal flow equation of microscopic scale under centrifugal force field

With the effects of surface force and viscosity change taken into consideration, a modified N−S equation for mold filling behavior of metal flow in micro-scale casting was developed in Ref. [16]:

$$u_x\frac{\partial u_x}{\mathrm{d}x}+u_y\frac{\partial u_x}{\mathrm{d}y}+u_z\frac{\partial u_x}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+g_x+\mu\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{\partial^2 u_x}{\partial z^2}\right)+\frac{2}{\rho}\frac{\partial\mu}{\partial T}\left[\frac{\partial T}{\partial x}\frac{\partial u_x}{\partial x}\right]-\frac{1}{\rho}\frac{\partial p_a}{\partial x}-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial x} \tag{2}$$

$$u_x\frac{\partial u_y}{\mathrm{d}x}+u_y\frac{\partial u_y}{\mathrm{d}y}+u_z\frac{\partial u_z}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+g_y+\mu\left(\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_y}{\partial z^2}\right)+\frac{2}{\rho}\frac{\partial\mu}{\partial T}\left[\frac{\partial T}{\partial y}\frac{\partial u_y}{\partial y}\right]-\frac{1}{\rho}\frac{\partial p_a}{\partial y}-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial y} \tag{3}$$

$$u_x\frac{\partial u_z}{\mathrm{d}x}+u_y\frac{\partial u_z}{\mathrm{d}y}+u_z\frac{\partial u_z}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+g_z+\mu\left(\frac{\partial^2 u_z}{\partial x^2}+\frac{\partial^2 u_z}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)+\frac{2}{\rho}\frac{\partial\mu}{\partial T}\left[\frac{\partial T}{\partial z}\frac{\partial u_z}{\partial z}\right]-\frac{1}{\rho}\frac{\partial p_a}{\partial z}-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial z} \tag{4}$$

where p_a is the gas counterpressure of the flow front; p_σ is the capillary forces between liquid metal and mold; g_x, g_y and g_z are the components of the volume force (gravity) in the x-, y-, z-direction, respectively.

The above equations indicate that the influence of the surface tension and the gas counterpressure cannot be neglected in micro-scale casting. Based on Eqs. (2)− (4), the N−S differential equations for liquid metal flow under centrifugal force have been developed.

Due to the assumption of constant viscosity (assumption 3), the 4th term on the right hand side of Eqs. (2)−(4) can be ignored. Also, the high permeability of gypsum has led to the gas counterpressure term (the 5th item on the right hand side of Eqs. (2)−(4)) to be ignored. Therefore, the modified Eqs. (2)−(4) can be obtained:

$$u_x\frac{\partial u_x}{\mathrm{d}x}+u_y\frac{\partial u_x}{\mathrm{d}y}+u_z\frac{\partial u_x}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+g_x+\mu\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{\partial^2 u_x}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial x} \tag{5}$$

$$u_x\frac{\partial u_y}{\mathrm{d}x}+u_y\frac{\partial u_y}{\mathrm{d}y}+u_z\frac{\partial u_y}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+g_y+\mu\left(\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_y}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial y} \tag{6}$$

$$u_x\frac{\partial u_z}{\mathrm{d}x}+u_y\frac{\partial u_z}{\mathrm{d}y}+u_z\frac{\partial u_z}{\mathrm{d}z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+g_z+\mu\left(\frac{\partial^2 u_z}{\partial x^2}+\frac{\partial^2 u_z}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p_\sigma}{\partial z} \tag{7}$$

where g_x, g_y and g_z are the components of the volume force (gravity, centrifugal force and Coriolis force) in the x-, y-, z-direction, respectively, and the other defined as before.

In the micro-scale vertical centrifugal casting process, the liquid particles subject to centrifugal force and thus move outwards from the center; in the meanwhile, the liquid particles subject to the Coriolis force. In the micro-mold cavity, due to the short moving distance on z-axis, less than 500 μm, the effect of gravity field in z-direction on the centrifugal flow can be